Radio Navigation Systems

FOR AVIATION AND MARITIME USE

A Comparative Study

Technical Editor
W. BAUSS

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CONTENTS

2.01. RADIO DIRECTION-FINDING ON BOARD AIRCRAFT AND SHIPS

W. T. RUNGE

1. GENERAL INTRODUCTION

RADIO direction-finding* is one of the oldest methods of radio navigation. Short- and medium-range radio direction-finding has been used in marine navigation since the twenties. The International Agreement on Safety of Life at Sea concluded in London in 1948[11] stipulates that all vessels of a gross tonnage of more than 1600 tons must be equipped with a radio direction-finder. See also Fig. 4.

Coast lines and air traffic areas are equipped only with special ground transmitters known as " radio beacons " (Fig. 4).

In aviation the instrument used for radio direction-finding is the radio compass.

The system has been developed to a high degree of perfection. Only with technological progress will the radio direction-finding equipment be reduced in bulk, and its operation be simplified and become more reliable.

2. SYSTEM DESCRIPTION

The voltage received by a rotatable loop antenna is zero when the plane of the loop antenna is perpendicular to the direction of propagation of the wave received (Fig. 1.1). Since the waves are propagated rather precisely
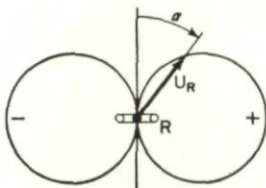
Fig. 1.1. Voltage R_R induced in loop (seen from above) as function of the angle between normal on the loop's plane and the direction of incidence α of the wave. Sharp zeros of induced voltage at angles $\alpha = 0°$ and $\alpha = 180°$.

along the great circle passing through the transmitter location, radial lines of position are thus obtained (cf. section 4). Frequently, an equivalent combination comprising a crossed-loop antenna and a goniometer (Fig. 1.2) is used in place of the rotatable loop.[1] In an aural null direction-finder,[8] the received voltage is adjusted to zero by aural observation and rotation of the

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* Note : The term " Radio direction-finding " as used in this paper is defined specifically as " determining the bearing of radio transmitting stations by means of an airborne or shipborne radio direction-finder ".

orientation of the loop antenna. The interfering influences of secondary radiators on the definition of the minimum observed with the aural null direction-finder (Fig. 1.3) are compensated by a voltage derived from an
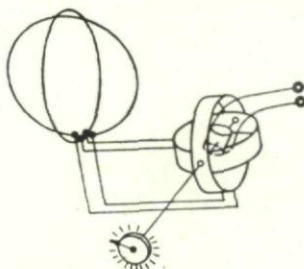
Fig. 1.2. *Crossed loops and goniometer.*
The voltage induced in the rotatable coil is equivalent to the voltage induced in rotatable loop at same angle of rotation.
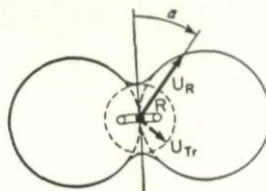
Fig. 1.3. *Superposition of voltage induced in ideal loop and omnidirectional error voltage UTR 90° out of phase.*
Blurred minima instead of sharp zeros of loop voltage U_R.

Sharpening of minimum
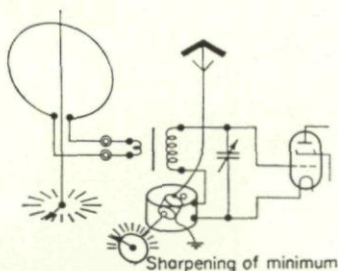
Fig. 1.4. *Input circuitry of direction-finder.*
A rotatable loop is closely coupled to the first tunable circuit. The coupling of the untuned auxiliary antenna can be varied for compensating the omnidirectional 90° degree out of phase error voltage.

omnidirectional auxiliary antenna, the magnitude and sign of which can be properly adjusted, "zero cleaning" (Fig. 1.4).

The rotatable loop of the radio compass[34]; or the search coil of the goniometer is adjusted automatically to the zero-position by a servo device (Fig. 2.2).

In the Watson-Watt direction-finder the inputs of two identical receivers are connected to the fixed crossed-loop antennas. The receivers supply two high- or intermediate-frequency voltages to a cathode-ray tube producing
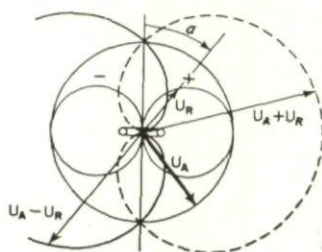
Fig. 2.1. *Superposition of loop voltage U_R and voltage of vertical antenna of equal phase and magnitude.*

Since the voltages corresponding to the two halves of the loop characteristic have opposite phase, the resulting diagram is kidney-shaped (cardioid). The two curves corresponding to the sum $U_A = U_R$ intersect at angles $\alpha = 0°$ and $\alpha = 180°$.
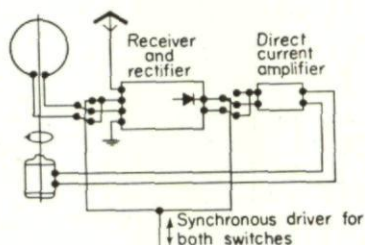
Fig. 2.2. *Principle of radio compass.*

The sense of rotation of the motor is determined by the position of the switch supplying the stronger signal. The motor turns the loop until the signal has the same amplitude for both positions. Only one of the two corresponding orientations of the loop being stable, the indicated direction is unambiguous.
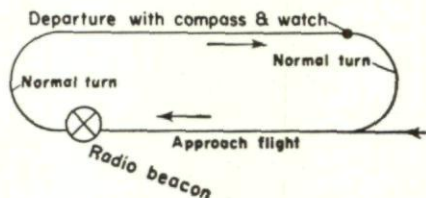
Fig. 2.3. *Waiting area in the vicinity of a radio beacon.*

there a straight line whose direction corresponds to that of the incident electromagnetic wave (Fig. 3).

When the polarization of the wave incident at the elevation angle e deviates by the angle k from normal polarization (horizontal magnetic field

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strength), the bearing error φ of the radio direction-finder is determined by the following equation: $\tan \varphi = \tan k \sin e$. In the case of the ground wave, e and k are zero. Therefore, the bearing error is also zero. In the case of sky waves, however, the polarization generally is not normal; both e and k differ from zero, the latter value being variable. When sky waves are received, bearings taken with the radio direction-finder, therefore, comprise an unsystematically fluctuating error whose magnitude may be substantial.[13]
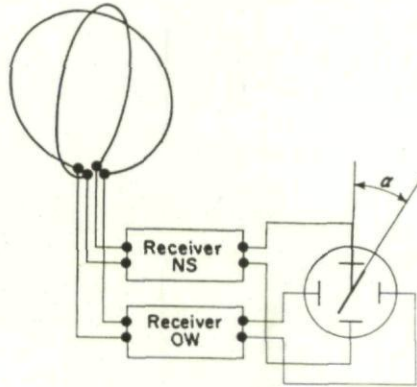
Fig. 3. *Watson–Watt's direction-finder.*
Two receivers having same amplification and phase shift furnish the received frequency or an intermediate frequency.
The presentation of both voltages on our oscilloscope produces a line, the direction of which corresponds to the direction of the incoming wave.

Bearings can be taken reliably only within the area where the ground wave predominates. During daytime and with frequencies below 300 kc/s, this range extends up to several thousand kilometres over sea water; at night, the range is reduced to approximately 100 km. The range reduces to less than 100 km at day and night with frequency increasing up to 4 Mc/s. With frequencies above approximately 2 Mc/s, reflections from nearby structures impair bearings; no useful bearings can be obtained with frequencies in excess of approximately 4 Mc/s.[6]

Attempts were made to eliminate the error caused by the rotation of the plane of polarization which occurs in the ionosphere, by transmitting pulses with steep leading edges and using only the first portion of the received pulse. This portion is due to the ground wave arriving earlier than the sky wave. However, for direction-finding these methods have not gained ground.

On wide unobstructed surfaces free from interfering reflectors, antenna systems can be constructed which will respond only to the normally polarized component of the radiation received (Adcock direction-finder). Such systems, however, fail on ships and aircraft since they are extremely sensitive to field distortions due to reflectors nearby.

For radio direction-finding no particular bandwidth requirement exists. Bearings can be taken even of unmodulated transmitters with zero bandwidth. Transmitters normally use a bandwidth of $\pm$ 1 kc/s, because identification must be provided either by modulation or by keying.

3. ACCURACY AND RANGE (COVERAGE)

The range (coverage) of radio direction-finding systems is limited not only by the requirement that the ground wave predominates (cf. section 2). It is also limited by the requirement that the field strength of the signal received must be greater than the atmospheric noise level at the receiver site. 50 μV/m are sufficient. This requires the following radiated powers over sea :

f	100 km	2000 km
kc/s	W	kW
50	0.3	1.0
100	0.3	2.5
300	0.3	22.0

The deviation from the great circle may be neglected in the case of ground waves over sea water.

The measuring accuracy of the receiver is limited by the equipment noise. The angle within which the signal is drowned by the equipment noise shall be less than $\pm$ 0.5° at a field strength of 50 μV/m. The centre-line of this angular sector can be estimated to approximately 1/10th of the width of the angle. In modern radio direction-finding receivers approximately 15 μV/m are sufficient for a minimum width of 1°. The systematic (quadrantal) bearing errors of up to approximately 20° caused by untuned conducting structures in the vicinity can be calibrated and compensated for. The standard deviation of the equipment bearing error of a compensated radio direction-finding receiver is less than $\pm$ 1°.

4. NAVIGATIONAL AND OPERATIONAL CONSIDERATIONS

4.1. *Navigational Considerations*

Radio direction-finding techniques supply the direction of the great circle on which the observed transmitter is located. It is, therefore, a suitable method of homing.

In order to determine the position, the true bearing will have to be obtained. North is supplied by the compass with a standard deviation of approximately $\pm$ 1°, therefore the standard deviation of the true bearing is approximately 1.4°. The true bearing can be plotted directly on the chart as a radial line of position through the transmitter when the distance to the transmitter is small. This procedure is permissible if the difference in longitude between transmitter and position is less than 2°, or if transmitter and position are located on different sides of the equator. Otherwise the curve connecting all loci of equal true bearing would depart too much from the great circle on which the transmitter is located. Corrections then will have to be taken from tables.[7]

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4.2. *Taking a Bearing*

At first the radio direction-finding receiver must be tuned to the transmitter.

4.2.1. When an aural null direction finder is used,[8,9] a zone of minimum reception is found by rotating the goniometer (Fig. 1.3). Then the zero sharpening control is adjusted so that reception is null in the centre of the minimum zone (Fig. 1.4). This position indicates the bearing relative to the longitudinal axis of the craft. The bearing scale frequently is a slave of the ship's compass. Then the bearing is read relative to magnetic or true north.

The bearing is perpendicular to the plane of the loop antenna. Therefore it is ambiguous. In order to eliminate ambiguity, the " Side Selector Switch " is placed into one of two positions marked by different colours. The colour of the position of minimum reception indicates the correct side on the bearing scale.

Since the minimum is observed aurally, the operator can judge the reliability and accuracy of the bearing taken. When several transmitters whose signals can be distinguished aurally are received simultaneously, a skilled operator can take bearings of both transmitters separately. This requires, of course, increased attention on the part of the operator; the accuracy is reduced.

While bearings are being taken, messages cannot be received simultaneously.

The aural null direction finder owes its popularity and extensive use to the possibility of judging the quality of a bearing directly, and to its simplicity.

4.2.2. The radio compass[3,4] need only be tuned ; no further manipulation is required. The loop antenna or the goniometer search coil is rotated automatically into the correct direction without ambiguity (Fig. 2.2). The bearing can be read directly from an instrument in the cockpit. Passing over the transmitter is indicated by a sudden change of the bearing from $0°$ to $180°$; approach and holding procedures use this marked indication (Fig. 2.3).

In aviation the radio compass is preferred because of its simple mode of operation, remote tuning control and remote data display. The operation of more recent types of equipment is even more simple by the use of crystal-controlled channels which can be selected within the frequency band at a 500 c/s spacing and which can be adjusted on a counter. The Model AD712 and AD360 (Marconi) are examples of such equipments. More recent instruments are transistorized.

While bearings are being taken, messages can be received simultaneously without interference.

The radio compass supplies unambiguous bearing information useful for remote display. The quality and reliability of a bearing taken can hardly be judged, for when several transmitters are received at the same time, the radio compass will indicate a bearing which cannot be identified with any one transmitter. It is a condition for the application of the radio

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compass that within the receiver bandwidth the frequency channel of the radio beacon on which a bearing is taken is left free of other transmissions. Fluctuating pointer deflections due to thunderstorms cannot be avoided.

4.2.3. The bearing obtained by means of a Watson–Watt direction-finder can also be read directly after tuning the receiver to the transmitter. Since a bearing error will occur when the amplifications of both receivers are unequal, equality of amplification will have to be checked and, if necessary, adjusted prior to taking a bearing. For this purpose both receiver inputs are connected in parallel. The tracer line should then indicate 45°. The angle obtained in taking a bearing is ambiguous. By operating the side selector switch, one half of the tracer line can be obscured.

While bearings are being taken, messages from the transmitter can be received without interference.

The Watson–Watt direction-finder combines direct indication of the bearing with the possibility of judging quality of the bearing by means of the picture on the cathode-ray tube screen. When two transmitters are received in the same channel both bearings are shown on the cathode-ray tube screen. This advantage is obtained at the expense of more costly equipment.

5. GROUND STATIONS AND AIRBORNE (SHIPBORNE) EQUIPMENT

5.1. *The Airborne (Shipborne) Equipment*

5.1.1. On ships, fixed crossed-loops are normally used which are either screened (area 0.7 m²) or free wire loops (area several m²).[2]

The receiver is connected to the crossed-loops by means of a two-pair core cable up to 30 m long.

The aural null radio direction-finder is extensively used on ships since it is a very simple piece of equipment comprising the goniometer and a sensitive and selective receiver. Prices, weight and dimensions of commercial equipment are listed in Table 4.3.

5.1.2. Also the Watson–Watt direction-finder is becoming more popular. The equipment comprises two receivers and a cathode-ray tube instead of the goniometer. The tracer line indicates the bearing which can be read from a scale provided around the cathode-ray tube. The bearing indicated either relates to the main axis of the craft or, if the scale is a Slave compass, to magnetic or true north. Prices, weights and dimensions of commercial equipment are listed in Table 4.3.

5.1.3. Recently Marconi developed a marine radio compass " Lodestar ", Model 2464A.[12] Since the stringent requirements of the Treaty on the Safety of Life at Sea[11] and of the regulations of several States based on the former cannot be met fully by the radio compass (see section 4.2.2, p. 24) it can be switched over to manual operation and then be operated as an aural null radio direction-finder. For price, weight and volume, see Table 4.3.

5.1.4. On aircraft, only the radio compass is used, because tuning to the respective transmitters is the only manipulation required. The bearing

can be read unambiguously from the instrument on the instrument panel. The antenna was formerly of the air-core frame type of approximately 20 cm diameter in a little streamlined dome. The next step of development was a ferrite coil system which is incorporated in a covered shallow recess in the skin of the fuselage. The radio compass DFA70 (Bendix) and AD7092D (Marconi) are good examples of this type of equipment. The most recent stage of development is a very flat ferrite crossed-loop with a miniature goniometer. This system avoids the mechanically complicated servo-controlled rotating loop in the fuselage skin. The Models AD712, AD722 and AD360 of Marconi and ADF102 of Lear are examples of this type of design.

5.2. *Ground Stations*

On the ground, radio direction-finding requires only transmitters of sufficient power and suitable frequency (cf. sections 2 and 3). The position of the transmitters must be known and identification must be easy. Since suitable commercial or broadcasting stations are not always situated in suitable locations and are not always radiating when bearings are required, radio beacons are provided in suitable locations. The power of such radio beacons as used in marine navigation is from a few watts to 100W, their frequency band from 285 to 315 kc/s. They are modulated and provide an identification signal. They are erected along the coast, especially also on lightships[7,10] (Fig. 4).
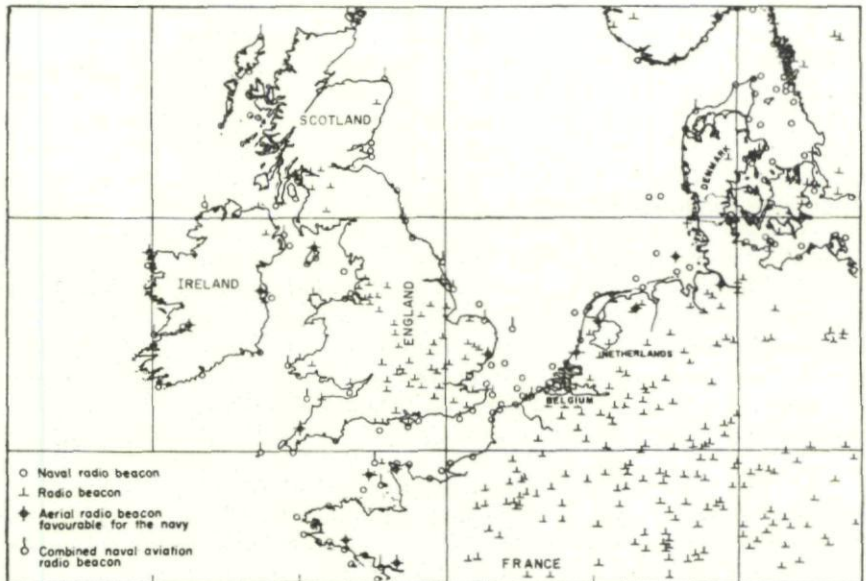

Fig. 4.

In aviation, keyed transmitters are used, operating in the 200–415 kc/s band, their power extending from 100 to 300W in individual cases up to 5 kW.

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